Collaborative Research on the Pelagic Ecosystem of the Southeastern Bering Sea Shelf

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ABSTRACT: Two Bering Sea marine research programs collaborated during the final years of the 1990s to forge significant advances in understanding of the southeastern Bering Sea pelagic ecosystem. Southeast Bering Sea Carrying Capacity, sponsored by NOAA Coastal Ocean Program, researched processes on the middle and outer shelf and the continental slope. Inner Front, sponsored by NSF, investigated processes of the inner domain and the front between the inner and middle domains. Program goals were to increase understanding of the southeastern Bering Sea ecosystem, including the role of juvenile walleye pollock, to investigate the hypothesis that elevated primary production at the inner front provides a summer-long energy source for the food web, and to develop and test annual indices of pre-recruit pollock abundance. Research took place during a period when there was unusually large variability in the marine climate, including a possible regime shift. Sea ice cover varied from essentially zero to one of the heaviest ice years in recent decades. Sea surface temperatures reached record highs during summer 1997, whereas 1999 was noted for its low Bering Sea temperatures. Moreover, coccolithophores bloomed on the shelf for the first recorded time, and these blooms now appear to be persistent. Integrated results include an archive of physical and biological time series that emphasize large year-to-year regional variability, and an Oscillating Control Hypothesis that relates marine productivity to climate forcing. Results suggest the need to examine confluences of interannual and even intra-seasonal variability with low-frequency climate variability as potential producers of major, abrupt changes in the southeastern Bering Sea ecosystem.

Keywords: Bering Sea, ecosystems, oceanography, marine biology, meteorology, climate, fisheries, marine mammals, seabirds

Two Complementary Research Programs

During the last five years of the 1990s, two research programs contributed jointly to the substantial marine research that has occurred over the last three decades on the southeastern Bering Sea. This region is an important continental shelf ecosystem that supports bountiful economic resources. It contains an abundance of high-latitude marine life and has one of the United States' busiest fishing ports supporting walleye pollock, salmon, halibut and crab fishing that generates over 2 billion dollars in revenue each year. The two coordinated research programs are Inner Front (InFront; 1997-2000), which was supported by the National Science Foundation (Prolonged Production and Trophic Transfer to Predators: Processes at the Inner Front of the S.E. Bering Sea), and Southeast Bering Sea Carrying Capacity (SEBSCC; 1996-2002), which was supported by the Coastal Ocean Program of NOAA (Wenzel and Scavia, 1993).

InFront and SEBSCC emphasized collaborative, interdisciplinary, regional studies and the importance of long time series in understanding variability of the Bering Sea. The programs complemented each other, as InFront was focused on the inner shelf and SEBSCC on the middle and outer shelf and the continental slope. Because several of the investigators in these two programs were involved with components of both studies, there was a strong incentive to collaborate and share data and ship time. As a result, both groups were able to leverage their resources and obtain a much more integrated understanding of processes on the shelf than would have been possible had the groups not collaborated in their field programs and analyses. The success of this integrated activity is borne out in the many multiple-authored papers contained in this and other issues acknowledging the support of both projects.

The goal of SEBSCC was to increase understanding of the southeastern Bering Sea ecosystem, to document the role of juvenile walleye pollock (***Theragra chalcogramma***) and factors that affect their survival, and to develop and test annual indices of pre-recruit (age-1) pollock abundance. SEBSCC was divided into monitoring, process, modeling, and retrospective and synthesis components focused on four central scientific issues: 1) How does climate variability influence the Bering Sea ecosystem? 2) What limits population growth on the Bering Sea shelf? 3) How do oceanographic conditions on the shelf influence biological distributions? 4) What influences primary and secondary production regimes? These broad issues supported SEBSCC's narrower goal of understanding the ecosystem in terms of pollock and provided a basis for selection of research components. SEBSCC also was envisioned as a source of information to support the regional fishing industry and its management. For example, results from SEBSCC research related to short-term forecast of pollock recruitment may improve stock assessments used to recommend "allowable biological catch" estimates to the North Pacific Fishery Management Council. Similarly, research results pertaining to the availability of juvenile pollock to apex predators could assist Council decisions regarding restriction of fishing around marine mammal rookery areas. SEBSCC's focus on ecosystem response to changes in environmental conditions provided a context for resource management in a changing environment.

SEBSCC research spanned disciplines from atmospheric physics to marine ornithology and addressed questions on scales ranging from atmospheric teleconnections to intimate associations between juvenile pollock and tentacles of jellyfish. The centerpiece of SEBSCC research was a time series of physical and biological data from an oceanographic mooring located in 70-m water at site 2 (Fig. 1). First deployed in 1995, the site 2 mooring measured vertical profiles of temperature and salinity and time series of currents and fluorescence year around. SEBSCC shipboard studies were repeated several times annually along transects from the Bering Sea basin to the 70-m isobath, then northwestward along this isobath (Fig. 1). One summer cruise and five fall cruises investigated the region around the Pribilof Islands that is believed to be an important nursery for young pollock. Annual, collaborative, summers cruise aboard the Japanese fishery training vessel ***Oshoro Maru*** enabled sampling and abundance estimates of juvenile pollock.

The InFront investigators hypothesized that elevated primary production at the inner front continues longer than production in the upper mixed layer of non-frontal waters, and that front-related production provides an energy source throughout the summer for a food web that supports short-tailed shearwaters (***Puffinus tenuirostris***), juvenile fish, and their zooplankton prey. Research focused on the role of the structural front between the well-mixed waters of the coastal domain and the two-layer system of the middle domain (Fig. 1). Three spring and three summer/fall cruises addressed the temporal and spatial variability of this system at four principal sites, as well as at several areas that were visited opportunistically. Each year millions of short-tailed shearwaters migrate from Australia to the Bering Sea to forage over the inner shelf. The evolution of this annual trans-equatorial migration implies that extraordinary amounts of prey must be readily available to these birds in the Bering Sea. Because earlier workers had described shearwater foraging as concentrated near the inner front, it was hypothesized that this region should support processes conducive to an unusually great abundance or availability of prey. This is also a region where young fish and some species of crab larvae congregate to forage.

To test this hypothesis, InFront investigators collected and interpreted observations on physical and biological features in the vicinity of the inner front. The project has shown that the inner front can facilitate the vertical flux of nutrients and, where this occurs, there is enhanced production at and near the front. Although data collection was restricted to the coastal regions of the southeastern Bering Sea, the results of InFront should be relevant to numerous continental shelf tidal fronts and ecosystems. Thus, the results have a general applicability to understanding and managing some of the world's most productive seas.

This special issue of ***Deep-Sea Research II*** presents results from the InFront and SEBSCC programs. The progress described here builds on research that has been summarized in earlier volumes. These include Hood and Kelley (1974), the Outer Continental Shelf Environmental Assessment Program (OCSEAP; Hood and Calder 1981), Bering Sea Marginal Ice Zone Experiment (MIZEX; Muench 1983), Processes and Resources of the Bering Sea Shelf (PROBES, Hood 1986), Mathisen and Coyle (1996), Bering Sea Fisheries-Oceanography Coordinated Investigations (BS FOCI; Macklin 1999) and Loughlin and Ohtani (1999). The work of the PROBES program defined the specific hydrographic regimes for the region (the coastal or inner shelf domain, the middle shelf domain, the outer shelf domain, the continental slope, and the transitional areas or fronts between them) that were addressed separately and jointly by InFront and SEBSCC. Each of these domains is a different marine habitat. Research reported in this special issue spans these hydrographic domains.

Research Setting and Integrated Results

InFront and SEBSCC were fortunate to conduct research during a period when there was unusually great variability in the marine climate and possibly a regime shift in the winter of 1998-1999. Sea ice cover over the southeastern Bering Sea shelf varied from essentially zero in 1996 to one of the heaviest ice years in recent decades in 1999. Sea surface temperatures were unusually high in late spring and summer of 1997, whereas 1999 was noted for its low temperatures. Coccolithophores bloomed for the first recorded time over the shelf in 1997, and these blooms now appear to be a persistent feature of the southeastern shelf. In the late 1990s, there was also marked variation in the abundance of coastal copepod species, suggesting that the variability in marine climate was transferred through the shelf food webs to the zooplankton. Evidence that the variability was of consequence to upper trophic level organisms was reflected in a massive die-off of short-tailed shearwaters in 1997, and in considerable variability in the strength of pollock year classes.

The ability to study a system during a period of great interannual variability helped to focus attention on mechanisms by which climate can affect the amount and fate of annual production over the shelf. The result was the development of a new hypothesis, the Oscillating Control Hypothesis (OCH; Hunt et al., This volume). OCH provides a rationale as to why the control of the recruitment of pollock and other large fish might shift from bottom up to top down with a change from a prolonged period of heavy ice years (cold regime) to a period of years with early ice retreat (warm regime). This variability also provided the opportunity to see how the southeastern shelf ecosystem might function if warmed by global change.

Variability in the southeastern Bering Sea shelf ecosystem was captured, at least in part, by the combination of descriptive and process studies in the InFront and SEBSCC programs. Thus far, this work has led to a set of five papers in ***Fisheries Oceanography*** (Vol. 10 No. 1, 2001), the present special volume of ***Deep-Sea Research II***, and a special volume of ***Progress in Oceanography***, now in press, that will encompass a wide range of recent research in the Bering Sea. In addition, numerous other papers originating from the programs have been published elsewhere.

Implications for the Future

From the work of InFront and SEBSCC, there is a growing appreciation that major, abrupt changes in the southeastern Bering Sea ecosystem may be precipitated by a confluence of events that pushes the system to a new state. These events that periodically reshape the southeastern Bering Sea may be the result of the combining of large interannual and even intra-seasonal variability with low-frequency variability to produce extreme events. For example, consider the coccolithophores that first appeared during the summer of 1997, and have persisted ever since, despite conditions that no longer appear to favor their prominence.

During spring and summer of 1997, atmospheric conditions over the eastern Bering Sea included uncharacteristically light winds, warm temperatures and clear skies. These conditions resulted from forcing on multiple time scales: intra-seasonal, El Niño, Pacific Decadal Oscillation, and global warming. The atmosphere affected the ocean, causing a cascade through the ecosystem. Although, the exact mechanisms associated with the cascade are not well understood, the following progression of events describes a plausible scenario: An early April spring diatom bloom associated with sea ice depleted nutrients in the upper layer. One lone wind event occurred in mid-May that mixed the upper 45-50 m, introducing nutrients from the lower layer into the upper water column. A consequent phytoplankton bloom further reduced the reservoir of nutrients typically found throughout the summer. Warm, nutrient-poor water set the stage for the switch from diatoms to a coccolithophore bloom unprecedented in recorded Bering Sea history. The coccolithophore bloom numerically dominated phytoplankton. A coincident inability of shearwaters to obtain their euphausiid prey, perhaps exacerbated by the clouding of the water by the coccolithophores, was indicated in the mass mortality of these seabirds. By contrast, 1998 was different in forcing, produced summer water conditions dissimilar to the year before, yet a similar coccolithophore bloom occurred. Each year since 1997, there has been a flourishing abundance of coccolithophores. They have occurred without a duplication of the meteorological and oceanographic events that first established the bloom. Thus, a physical event, sea ice in April coupled with calm winds and clear skies, produced a major ecosystem change, the coccolithophorid bloom, with repercussions up the food chain for several subsequent years.

So-called regimes often have their largest ranges near the time of their major shifts. The ecosystem can be reorganized during such events and the persistence of biological processes can prolong the reorganization after the physical system is shifted to more routine behavior. Such events may be occurring on decadal scales as well. For the previous two decades, the Southeast Bering Sea ecosystem has had a dominant pelagic species, the commercially fished walleye pollock. Pollock is a nodal species, constituting an integral part of the region's food chain as both prey and predator. The strongest year classes were in 1978 and 1989. These were both periods of regime shifts where there was a dramatic change in wind forcing of the Bering Sea. Future research on the connections between climate and marine ecosystem function will need to examine the processes that link atmospheric forcing and the processes that control the amount and fate of production.

SEBSCC and InFront have extended the knowledge base of the southeastern Bering Sea at a critical moment. Increasing attention is being focused on the Bering Sea. Just a few years ago, while other fisheries of the United States were suffering serious declines, the eastern Bering Sea fishery was considered stable. In the past several years, there have been indications that this may not be the case. Commercial salmon failures, curtailment of fishing areas and times because of declining marine mammal populations, massive numbers of seabird deaths, and indications that a shift in springtime Bering Sea climate may be occurring, all suggest that the Bering Sea ecosystem is changing in a significant way. It is clear that we must understand these changes to enable responsible management of regional resources. These two programs, InFront and SEBSCC, have contributed long-term measurements and results described in this special issue that are important to a more complete comprehension of the complex Bering Sea ecosystem.

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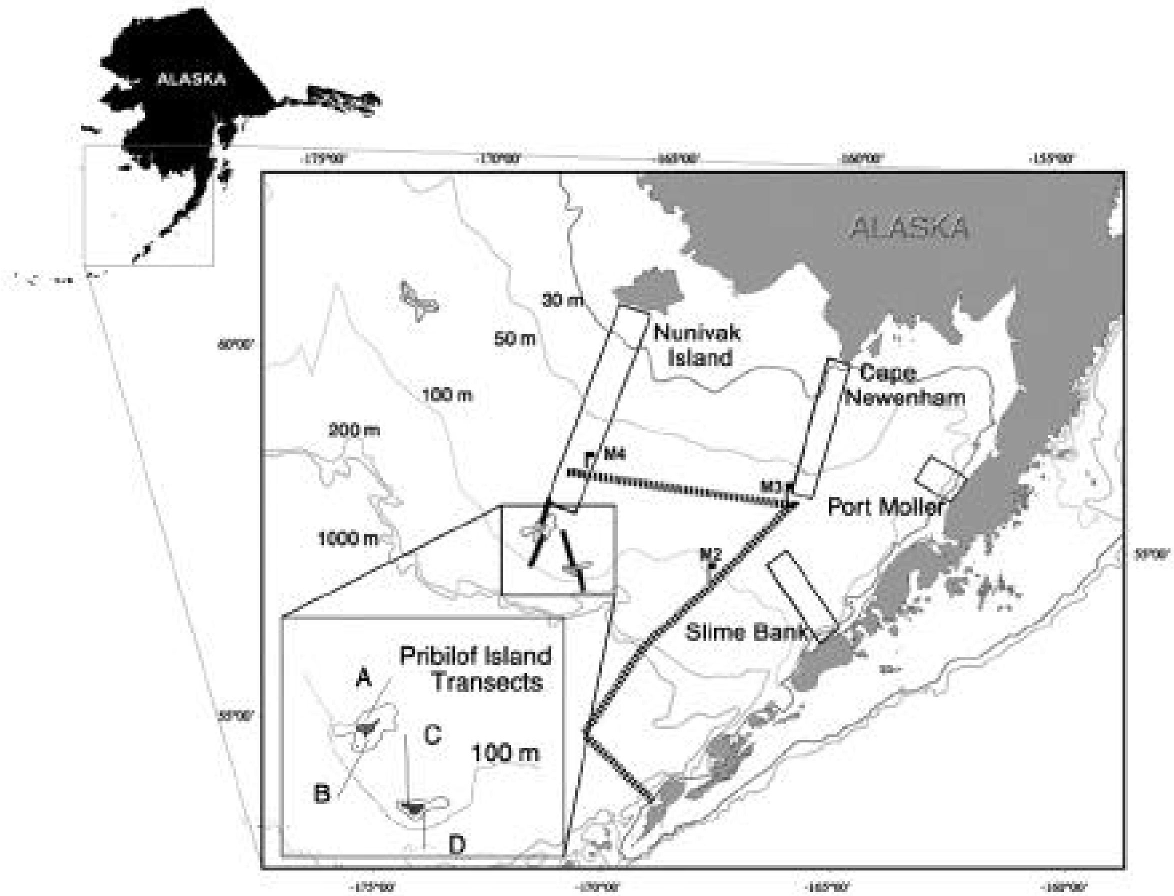

Figure 1. A bathymetric map of the southeastern Bering Sea shelf shows the location of study areas investigated by the Inner Front (InFront) and the Southeastern Bering Sea Carrying Capacity (SEBSCC) programs. The dashed lines indicate transects covered by SEBSCC at least twice yearly when servicing the moorings at M2, M3, and M4. Transects A, B, C and D at the Pribilof islands were visited yearly in the fall and once in the summer by SEBSCC cruises. Rectangles at Nunivak Island, Cape Newenham, Port Moller and Slime Bank mark the locations of the principal study sites occupied during the InFront study. Collaborative summer cruises with Japanese researchers sampled juvenile pollock over an area similar to the Pribilof Island inset. (Illustration from Napp and Hunt, 2001)